Mechanical behavior modeling in the presence of strain aging

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MECHANICAL BEHAVIOR MODELING IN THE PRESENCE OF STRAIN AGING

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ABSTRACT

Piobert-Lüders phenomenon is modeled by means of simplified local constitutive equations implemented in a finite element software. A local softening behavior allows simulating the formation of localized strain bands and the development of a Lüders plateau on the stress strain tensile curve. The influence of various parameters of the numerical model are investigated: meshing, behavior law and boundary conditions. This study shows that all the characteristics of the stress – strain curve plateau cannot be deduced only from the local intrinsic behavior: the plateau also depends strongly on the geometrical constraints applied on the specimen.

Introduction

Many structural materials are subjected to strain aging, which causes inhomogeneous yielding such as Piobert–Lüders' bands and Portevin – Le Châtelier (PLC) instabilities. These phenomena occur in steels containing interstitial elements in solid solution such as carbon or nitrogen, which segregate to dislocations thus inducing dislocation pinning. Even though the physical origin of strain aging has been widely studied, its influence on the fracture toughness of steels remains discussed. In order to further study the influence of strain aging on fracture toughness, the identification of a strain aging model is necessary. Two classes of models are able to simulate the behavior of materials which are sensitive to strain aging. A first class of models takes into account the physical origin of strain aging: pinning of dislocations by solute atmospheres that diffuse during strain [1]. These kinds of constitutive models have been expressed as behavior laws which can be implemented in finite element simulation software [2], and allows the simulation of both Lüders and Portevin – Le Châtelier (PLC) instabilities. The second class of models, more phenomenological, can also simulate static strain aging and the Lüders bands. As suggested by Tsukahara and Iung [3] the strain localization of the Lüders band is made possible by introducing a phenomenological local softening behavior.

We have performed a preliminary study by taking into account only static strain aging. In the perspective of identification, the local behavior has to be chosen in order to be related to experimental stress – strain curves. The first step is to understand the transition from the local behavior to the global stress – strain curve. Therefore a numerical simulation of strain localizations during tensile tests has been undertaken and a special attention has been devoted to characterize the influence of the various parameters of the numerical model: meshing, local constitutive equations, boundary conditions.

Numerical procedure for finite element modeling of Lüders' band

In a context of identification of constitutive models, we need to correlate model parameters to experimental data of the tensile test. However, the identification of the model parameters highlights a difficulty in the case of static strain aging: how to manage the identification in the presence of a Lüders' plateau on an experimental stress-strain curve?

In experiments, stress – strain curves affected by Lüders phenomenon takes the form of curve a) in figure 1. The Lüders peak, also called "upper yield stress", can be locally interpreted by the overstress necessary to move the dislocations, which are initially pinned by solute atoms. When the unpinning stress is reached, the dislocations suddenly break away from their solute atmospheres: this avalanche of dislocations causes the strain localization. The Lüders band propagation is associated on the stress – strain curve to a plateau at nearly the constant stress σ_L, also called "lower yield stress".

In strain aging models that simulate Lüders strain localization, the local behavior is always described by a softening: the stress first rises up to σ_{max} and then drop to σ_{min} at the strain value ε_{min}, as shown in Figure 1b.

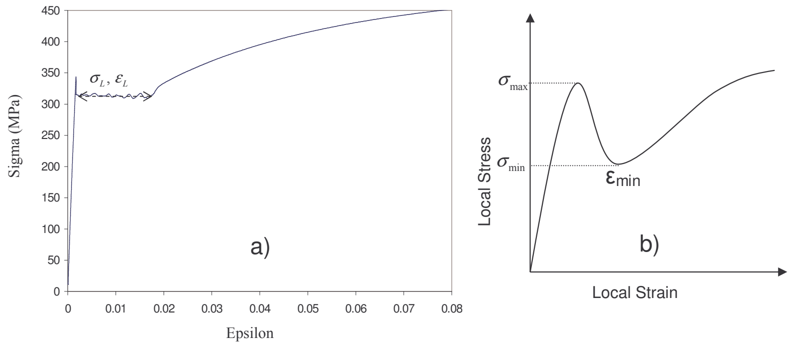

Figure 1: Macroscopic stress-strain curve from tensile test (a), and local material behavior (b).

Therefore, it is necessary to understand how the intrinsic behavior (characterized by σ_{max}, σ_{min} and ε_{min}) can be linked to the macroscopic manifestations of static strain aging on a specimen in experimental conditions (σ_L and ε_L). Within a more general framework, this work will also give a good methodology for identifying any model giving the flow stress in the presence of a Lüders plateau.

To manage the numerical study of the Lüders phenomenon and to check the influence of the parameters of the numerical model on the macroscopic behavior, the tensile tests are simulated on rectangular flat specimens. For the sake of simplicity unpinning mechanisms is described by a simplified local constitutive equation that allows only simulating static strain aging [3] (no temperature and strain rate dependencies). The aging process is introduced by an overstress necessary to the dislocation unlocking mechanism: at yield point (σ_{max}), the stress drops down to σ_{min} and then follows an isotropic strain hardening behavior, as shown in Figure 2. This local softening gives rise to strain localization and Lüders band initiation and propagation. Two forms of softening behavior have been tested in the present study. The first one, as illustrated in Figure 2a, is obtained with a non linear isotropic strain hardening law R(p), defined as followed :

$$\begin{aligned} &R(p) = R_0 + Q_1\left(1-\exp\left(-b_1 p\right)\right) + Q_2\left(1-\exp\left(-b_2 p\right)\right) \\ &\text{with } Q_1 < 0 \ et \ Q_2 > 0 \end{aligned} \tag{1}$$

The second one (Figure 2b) is composed of linear evolutions of the flow stress.

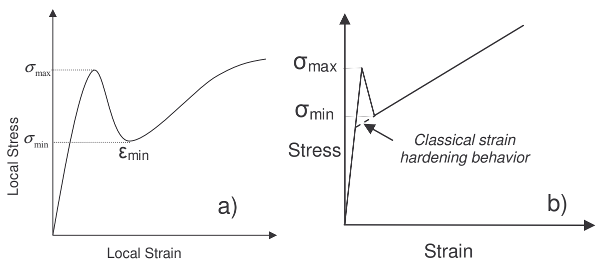

Figure 2: Two local behavior laws used to simulate Lüders' bands. Introducing local softening allows strain to localize.

The tensile specimen (2.5 x 12.5 mm^2) has been first modeled by a regular mesh of 500 elements. The geometry of the specimen allows using a 2D model with plane stress conditions. Eight nodes elements with reduced integration are used. The vertical displacement of the bottom is fixed to zero. Tension is imposed through the displacement of the top nodes at constant displacement rate. One node on the bottom and one node on the top are chosen to represent the tensile axis: their horizontal displacement is fixed to zero.

In experiments, the Lüders bands are triggered by geometry imperfections, such as sample fillet, or by material imperfections, such as inclusions or large grains. These imperfections cause local stress concentrations responsible for plastic strain initiation. In our simulations, when using a regular mesh the introduction of an artificial defect is necessary to trigger strain localization. We have represented imperfections by introducing a geometrical defect with a local modification of the width of the plate, or by introducing an element with a lower yield stress.

Analysis of the propagation of the Lüders bands

The numerical simulation of the tensile test is exposed in Figure 3 with the local behavior law plotted in dotted line. It shows that, when the flow stress is reached, the plastic strain appears at the artificial defect introduced here at the right bottom corner of the sample. Then the specimen exhibits a strain localization band oriented about 50° from the tensile direction (Figure 3b). This plastic band progressively fills the whole specimen. The band spread is related to a plateau at nearly constant stress on the stress - strain macroscopic curve (Figure 3a).

In order to best characterize the Lüders plateau the stress variations observed have been correlated to the propagation of the Lüders bands: each stress drop on the stress – strain curve can be related to a special feature on the band progression.

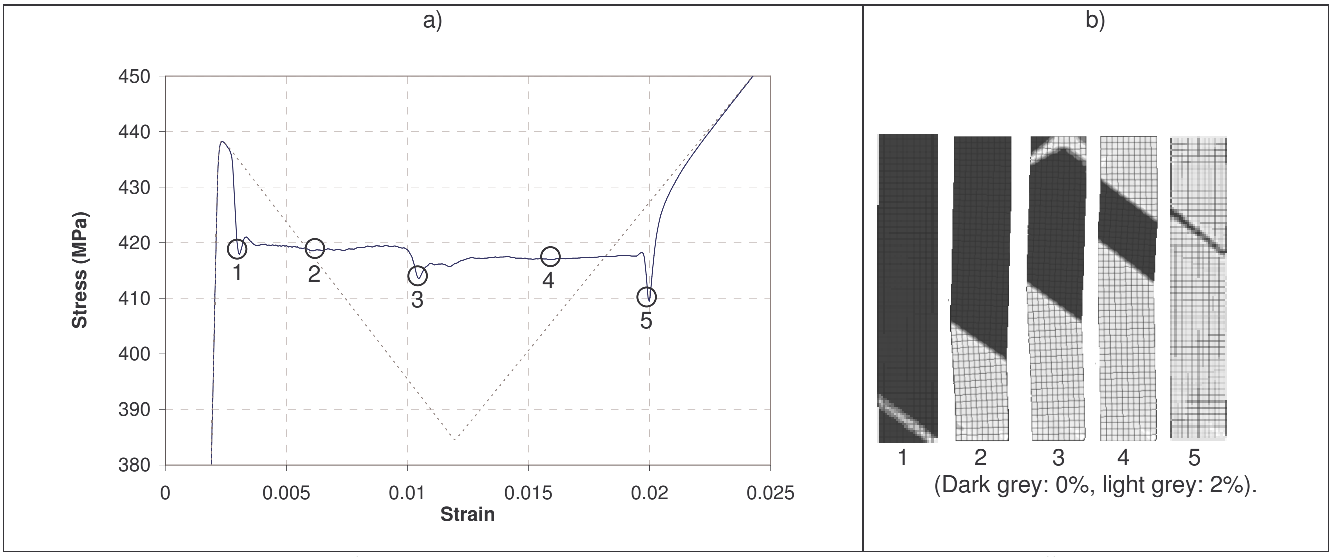

Figure 3: Analysis of the Lüders plateau: equivalent plastic strain on the specimen at different stages

When the stress reaches the maximum, the strain starts to localize. This first yielding occurs at a stress concentration point, caused by a specimen geometrical singularity. The global stress starts to drop when the first plastic strain band crosses the specimen width. The global stress reaches the minimum when the band has totally crossed the specimen (picture 1). Locally, at the band front, the stress reaches the yield point thus allowing further propagation of the band. After the first band has developed, the plastic zone is also affected by an elastic unloading. The nucleation of a new band (for example because of geometrical constraints) causes a stress drop on the stress – strain global curve (picture 3). Then the two bands propagate alternatively and a stress drop is observed when the two bands merge (picture 5). The final strong increase of the stress corresponds to elastic re-loading of the whole specimen. The global behavior recovers the local behavior when the peak stress is reached in every point of the sample.

It can be concluded that the Lüders plateau characteristics result from the localized plasticity propagation and its coupling with the global geometrical constrain of the specimen. Only two strain states are possible: the elastic state where the band has not yet come through and the plastic strain associated to the coincidence between global and local behavior. Consequently, all the characteristics of the stress – strain curve plateau cannot be deduced only from the local intrinsic behavior. Nevertheless, the stress variations can be related to some details of the band progression features.

Influence of model parameters on the Lüders plateau

In order to check the influence of the parameters of the numerical model on the macroscopic behavior, different simulations of tensile tests have been performed. The influence of three groups of parameters has been studied: local behavior law, meshing and boundary conditions. The length, as well as the stress level of the Lüders plateau obtained for these different parameters, will be compared in order to determine which parameters have a predominant influence and to test the links that could exist between the local and macroscopic behavior.

Influence of the local behavior law

We have first studied the influence of the local behavior law on the Lüders plateau, in order to try to find a correlation between the plateau stress level and the parameters of the model.

Six different bi-exponential plastic laws were tested, varying the amplitude of the softening, i.e. the value $\sigma_{max} - \sigma_{min}$, and varying ε_{min}, the plastic strain associated with the minimal stress. For all simulations, the upper yield stress (Lüders peak) on the global stress – strain curve is very close to σ_{max} imposed in the behavior law. The stress level (σ_L) of the simulated plateau has been compared to the maximal and the minimal stresses of the local behavior law. The relative level of the plateau varied from 20 % to 32 % of $\sigma_{max} - \sigma_{min}$ with a mean value close to 25 %. Figure 4 shows two examples of local constitutive curves and corresponding macroscopic stress – strain evolutions.

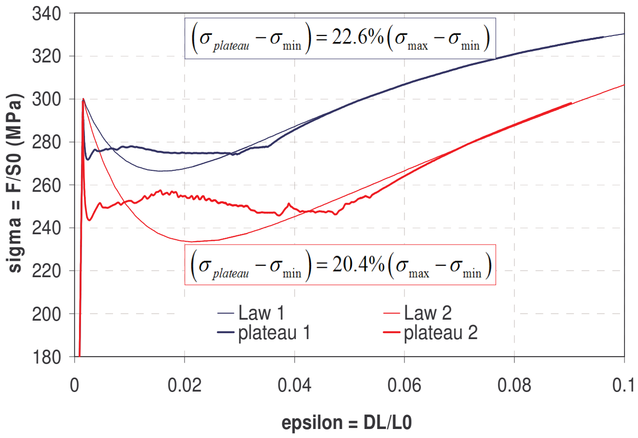

Figure 4: Influence of the behavior law on the plateau stress level

We can note that the plateau length depends on the amplitude of the softening: the larger the softening, the longer the plateau. However, the position of ε_{min} does no seem to have any influence on the plateau length.

A similar study has been performed using the bi-linear behavior law. The stress level of the plateau differs notably from the exponential law: the average level is around 40 % of $\sigma_{max} - \sigma_{min}$. (curves not reported).

So the length of the Lüders plateau can be roughly approximated from the imposed amplitude of the softening. However, the stress level of the plateau on the stress-strain curves is not totally representative of the local softening behavior of the material. We have thus investigated the influence of two other groups of parameters on the Lüders plateau: meshing and boundary conditions.

Influence of meshing

The mesh dependency of Lüders modeling has been investigated. It is well known that numerical simulation of strain localization is influenced by the mesh size. So two regular meshes of different size (500 elements and 2000 elements) and a free mesh with local variations of mesh size (3500 elements) have been tested. The aim is to show how the localized band can progress in this more heterogeneous environment.

As shown in Figure 5, the mean stress level of the plateau changes slightly with these three meshes, as well as its length. The finer the mesh, the longer the plateau, the higher the stress level of the plateau. Furthermore, with the random mesh, the plateau stress is not constant. This jerky flow can be attributed to the mesh heterogeneities, which induce local stress concentrations thus making the propagation of the Lüders band more discontinuous.

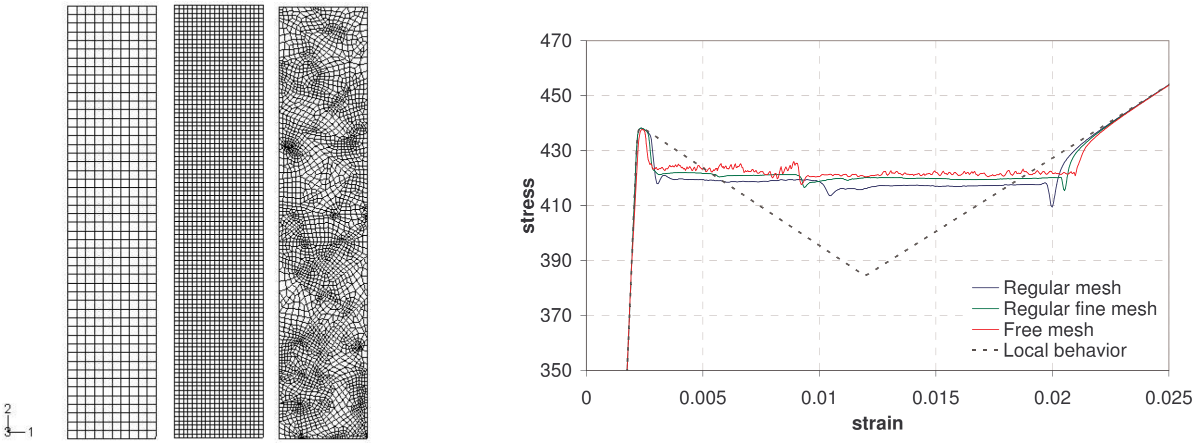

Figure 5: Influence of meshing on Lüders plateau modeling: different meshes (left) and corresponding Lüders plateau (right).

As shown in Figure 6 obtained with a random mesh it is possible to initiate the localization band without introducing a local defect. After being homogeneous in the major part of the softening stage, the strain starts to localize at about the minimum stress (only 0.006 % of localized strain). The plastic strain maps reported in Figure 6 show the chaotic band propagation: secondary bands initiate and propagate at the front of the master band. It is worth noting that this discontinuous band propagation is very similar to the experimental observations [4-7].

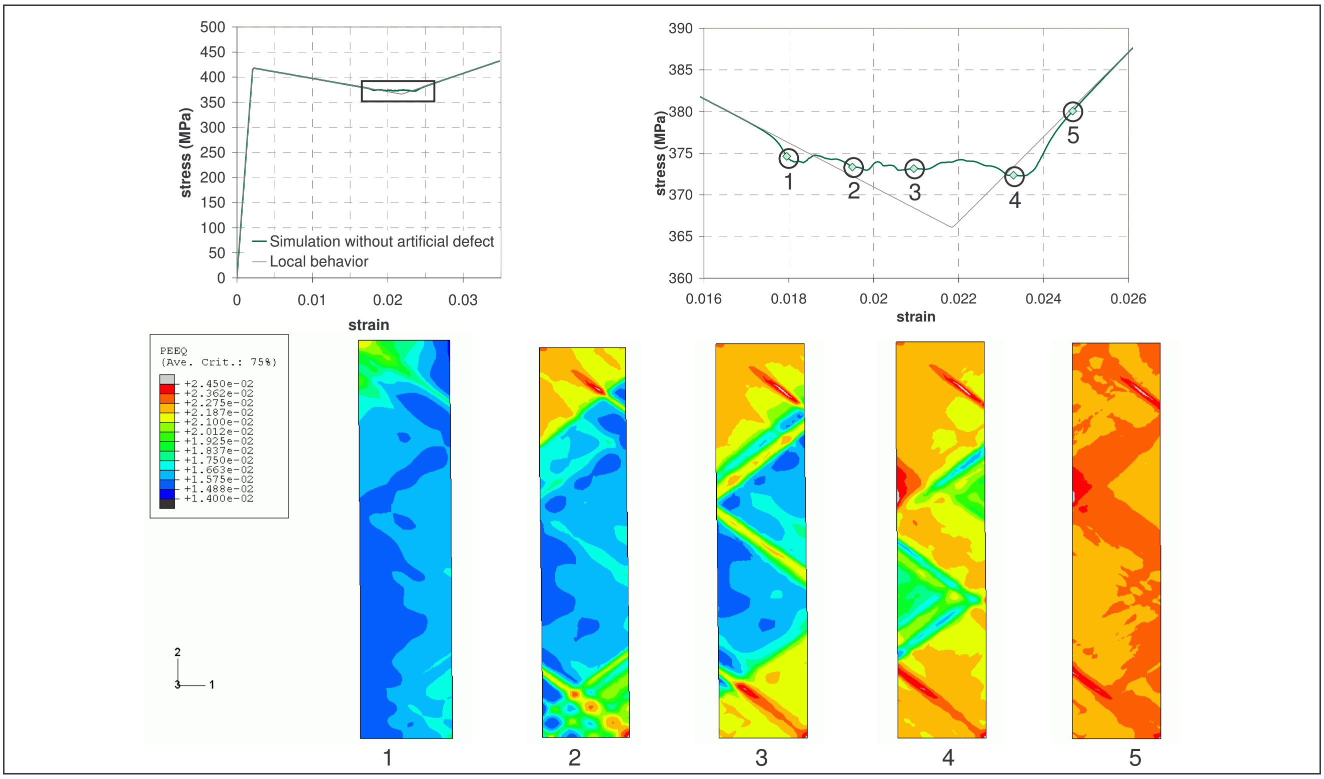

Figure 6: Lüders band developing without artificial defect (isocontours of equivalent plastic strain)

Influence of artificial defect

As seen in the above simulation, the stress level and the length of the plateau are very different when no initial defect is introduced; the strain localization is delayed, thus inducing a shorter and lower plateau. The influence of the type and localization of the artificial defect has therefore been investigated. Five different geometrical defect locations, reported in Figure 7, have been tested. Each geometrical defect is introduced by a prescribed distortion of one or two elements obtained by displacing one node of the mesh. The geometrical defect located in the centre of the specimen leads to a hole in the mesh.

The same locations have also been tested introducing a “behavior defect” with a lower yield stress in the element of the mesh. The plateaus obtained for the defects located in a corner (3 and 5), are identical whatever the defect (curves not reported). For the other locations, the results are variable. The simulated plateau resulting from defect locations1, 2 and 4 are presented in Figure 7.

Plateaus resulting from defect location 1 are not very different from those obtained with defects located at the corners (3, 5). We can only note that the plateau obtained with the geometrical defect is particularly flat compared to the others. This can be explained by the fact that in this simulation, the band propagation is perfectly symmetric. We will discuss later in more details the relations between band propagation and plateau curve.

The simulation with geometrical defect 2, i.e. a hole in the centre of the sample, reveals a very early localization inducing a mean stress level higher than for other plateaus. The oscillating level of the plateau can be associated to the jerky propagation of Lüders bands in V-shape. Indeed the localization starts with an X shape from the middle of the specimen, and because of the symmetric configuration, the band front propagates alternatively in the upper and lower part.

Defect 4 leads to the more atypical Lüders plateaus. In this case, many constraints are prescribed at the same place: boundary conditions, defect, and symmetry conditions. Like in the precedent case, the band propagates with V-shape front, starting from the defect at the bottom and spreading up to the top. This jerky progression leads to an oscillating stress level.

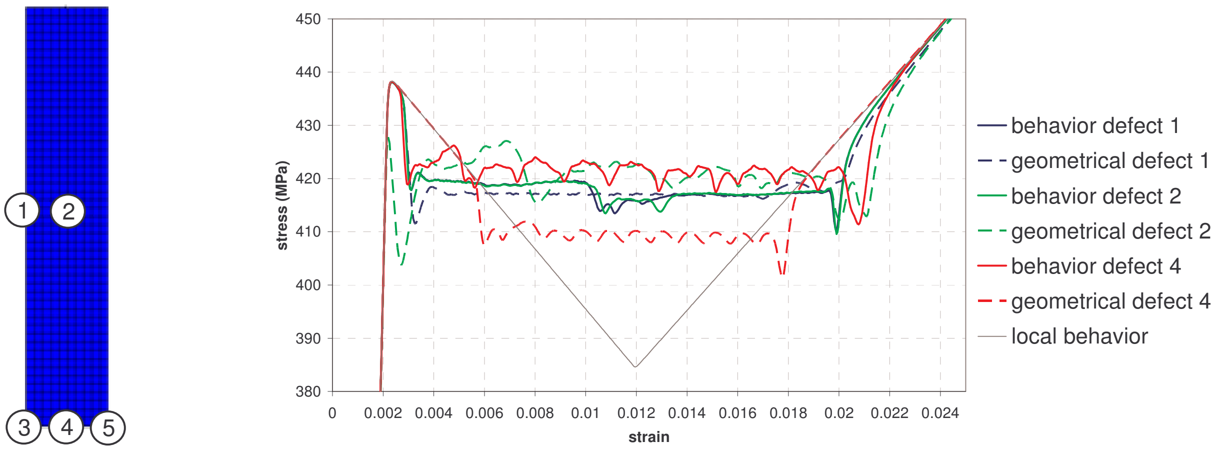

Figure 7: Influence of different defect types on location on the Lüders plateau

From this study devoted to the influence of artificial defects on Lüders band propagation, it can be concluded that the Lüders plateau is not only sensitive to the mesh, but also to the way the Lüders band is being initiated. Introducing an artificial defect exerts a large influence on the stress plateau level. The type of defect can modify the stress level up to 40% of $\sigma_{max} - \sigma_{min}$. In all cases, a geometrical defect seems to be more severe than a behavior defect. Symmetric conditions lead to an oscillating plateau and a jerky progression of the Lüders band. An early localization leads to an upper and longer plateau whereas a delayed localization leads to the opposite.

Influence of boundary conditions

In usual experimental tests, the boundary conditions applied on the specimen are not clearly defined all along the test, especially due to the geometrical uncertainties of the experimental setup. Different modeling conditions may be chosen depending on the hypothesis prescribed for the degree of freedom of upper ad lower nodes in the transverse direction. Two extreme choices can be made: entirely free, or entirely fixed. The results of the simulations with these two boundary conditions are presented in Figure 8.

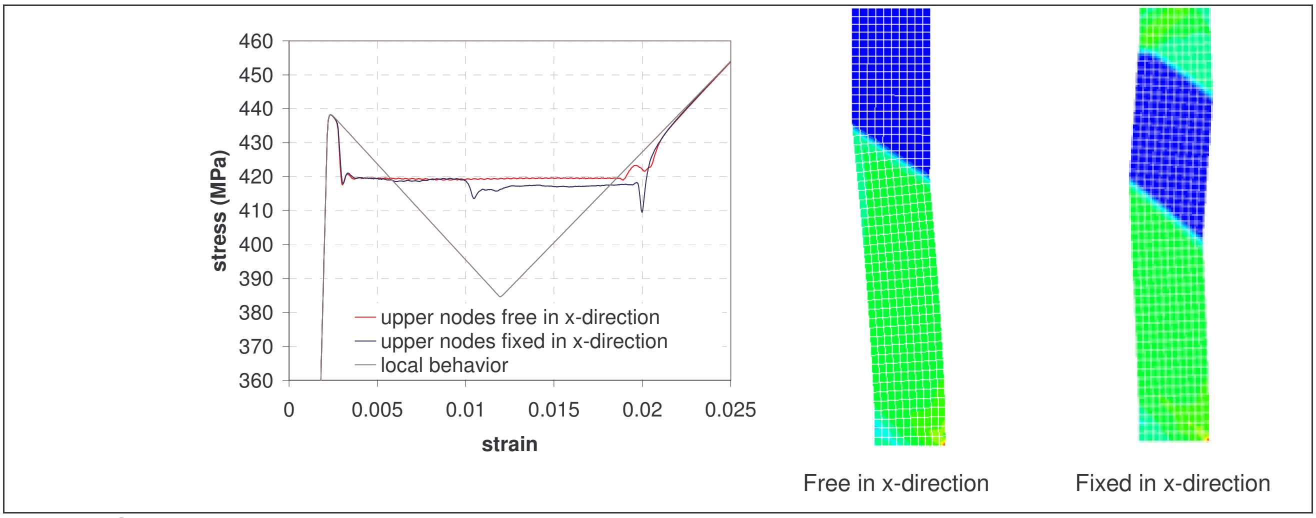

Figure 8: Simulation results with and without constraint in the transverse direction and related plastic strain band propagation

When the upper nodes are free in the transverse direction, only one band is developed and the plateau remains at constant stress. When a constraint is applied, the global distortion of the specimen generated by the 50° oriented strain band forces the initiation of a second band, in order to compensate the distortions. The stress drop on the plateau can be clearly associated to the triggering of this second band.

The more significant effect of boundary conditions on the plateau is obtained while simulating a test at prescribed force with constant stress rate. The results of the two simulations obtained with prescribed displacement or prescribed force respectively are presented in Figure 9.

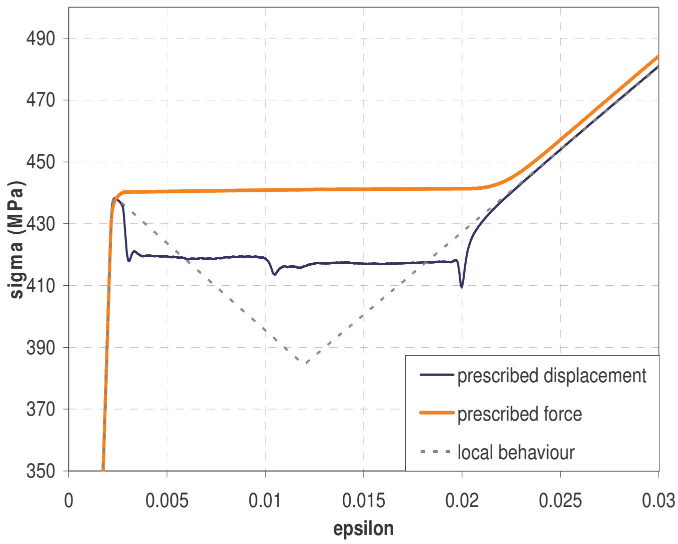

Figure 9: Comparison between tensile test results with prescribes displacement and force

Under prescribed forces, there is no Lüders peak. When the stress reaches the σ_{max} level of the local behavior law, it remains at constant level. The carried strain of the band is exactly equal to the strain necessary to recover the classical strain hardening behavior after the softening stage.

To conclude on the parametric study, these results demonstrate that the plateau level and length are not intrinsic parameters. They cannot be directly related to the local behavior. Many parameters influence the stress level of the Lüders plateau in imposed displacement. In fact, each simulation case gives a different plateau. The band seems to “choose” its path according the current constraints (mesh, defect, boundary conditions…). In consequence, each path of the localization band gives a particular plateau.

Conclusion

This study has shown that a simplified softening behavior law allows to simulate the main features associated to static strain aging. Nevertheless all the characteristics of the stress – strain curve plateau cannot be deduced only from the local intrinsic behavior. The Lüders plateau is not only sensitive to the mesh, but also to the boundary conditions and the way the Lüders band is being initiated. Introducing an artificial defect exerts a large influence on the stress plateau level.

From the tentative correlation between the local and global behavior it can be concluded that he maximum stress of the local law can be approximately related to the measured macroscopic peak stress. The length of the plateau corresponds roughly to the plastic strain for which global and local behavior coincide.

The simplified law used in this study well simulates Lüders behavior but remains a phenomenological law. It does not take into account the physical origin of strain aging, is not temperature and strain rate dependant and does not simulate dynamic strain aging. So, to further understand the influence of static and dynamic strain aging on fracture toughness, it will be necessary to identify and apply the McCormick - Zhang model [2] to fracture geometry specimen, to further predict the loss of fracture toughness in the presence of strain aging.

References

1. Kubin, L.P., Estrin, Y., “Dynamic stain ageing and the mechanical response of alloys,” J. Phys., III-1, 929-943 (1991).
2. Zhang, S., McCormick, P.G., Estrin, Y., “The morphology of Portevin – Le Châtelier bands: finite elements simulations for Al-Mg-Si,” Acta Mater., **49**, 1087-1094 (2001).
3. Tsukahara, H., Iung, T., “Finite Element Simulation of the Piobert-Luders behavior in an uniaxial tensile test,” Mat. Sc. & Ing., A248, 304-308 (1998).
4. Nadai (A.), “Theory of Flow and Fracture of Solids,” McGrow W-Hill Compagny, chap.16 (1931).
5. Jaoul, B., “Etude de la plasticité et application aux métaux,” Dunod Ed. (1964).
6. McClintock, F.A., “Mechanical Behavior of Materials,” Addison – Wesley Publishing Company (1966).
7. Soler, M., “Etude du Vieillissement d’un acier à Bake-Hardening : évolution des propriétés mécaniques de traction – corrélation avec la microstructure,” PhD thesis, INSA Lyon (1998).
8. Baird, J.D., “Strain Aging of Steel – a critical review,” Iron & Steel, 1963